De Sitter Dialectics

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based on
JHEP 09 (2022) 208 and 2306.07332
with Bruno Bento, Dibya Chakraborty and Ivonne Zavala
and work to appear with Joaquim Gomes and Ed Hardy

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  Anti-thesis = metastable dS vacua are possible in QG?
  Synthesis = transient dS vacua are possible in QG?

Plan

- Some recent questions around KKLT/LVS constructions
- Weakly-warped LVS de Sitter solution
- Robustness against g_s and $\mathcal{V}$ corrections
- Transient de Sitter from interacting Dark Sectors

Uplifting without runaways

KKLT ’03; see also Bena, Dudas, Grana & Lüst ’18; Lüst & Randall ’22

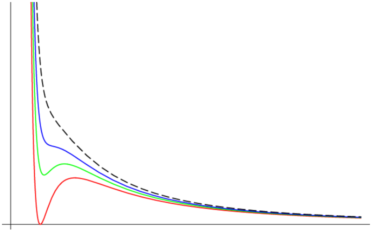

Figure from Anguelova, Calo, Cicoli ’09

- In KKLT/LVS, stabilisation via balance of classical, perturbative and non-perburtative effects and uplifting by e.g. $\overline{D}3$-brane.

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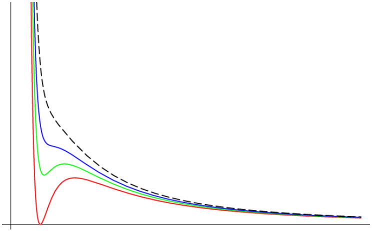

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- Uplifting must not destabilise volume modulus – place $\overline{D}3$-brane at tip of strongly warped throat – large flux numbers $MK \sim \mathcal{O}(100) - \mathcal{O}(1000)$ – large contributions to tadpole, which must be cancelled.

Bena, Blaback, Graña & Lüst '20; Crinó, Quevedo & Valandro '20

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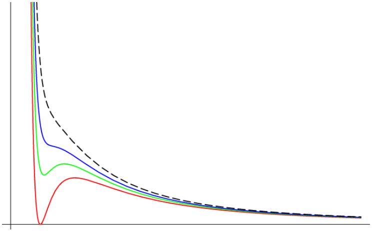

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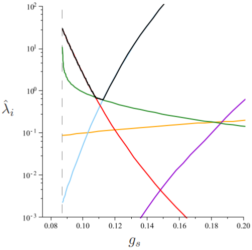
- Alternative may be to have weak warping and large AW_0 in $W = W_0 + Ae^{-aT}$.

String-loop and curvature corrections

Junghans '22



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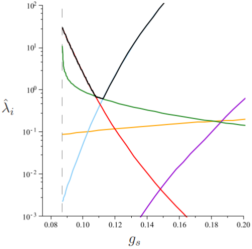

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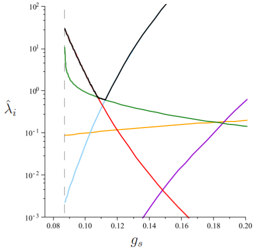

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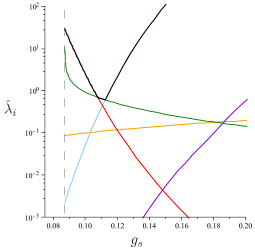

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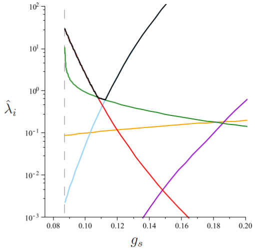

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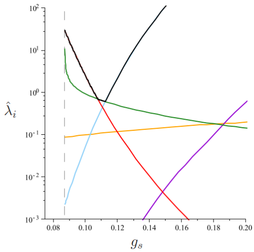

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- Remaining corrections cannot be simultaneously parametrically suppressed in small g_s and large $\mathcal{V}$.
- Consistency of LVS relies on suppression of some numerical coefficients, which should be computed...
- Weak warping and low *MK* may help to suppress α' corrections.

Weakly warped deformed conifold

Bento, Chakraborty, SLP, Zavala '23

- Type IIB flux compactification with warped deformed conifold region glued to compact CY:

$$ds^2 = h^{-1/2} g_{\mu\nu} dx^\mu dx^\nu + h^{1/2} c(x)^{1/2} g_{mn} dy^m dy^n$$

with warp factor $h \equiv 1 + \frac{e^{-4A_0(y)}}{c(x)}$ and $c(x) = \mathcal{V}^{2/3}$.

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- Warped throat region $h \gtrsim 2$; weakly warped region $1 \lesssim h \lesssim 2$.
- Near the conifold tip, with deformation parameter ϵ and $R_\epsilon^2 \sim \epsilon^{4/3}$:

$$ds_{10}^2 = h^{-1/2} g_{\mu\nu} dx^\mu dx^\nu + h^{1/2} c(x)^{1/2} \left(dr_0^2 + \frac{r_0^2}{8} d\Omega_{S^2}^2 + R_\epsilon^2 d\Omega_{S^3}^2 \right)$$

with $e^{-4A_0(\eta)} = 2^{2/3} \frac{(\alpha' g_s M)^2}{\epsilon^{8/3}} I(\eta)$ and $\frac{1}{(2\pi)^2 \alpha'} \int_{S^3} F_3 = M$.

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- For weak warping, physical radius at tip: ${R_{S^3}}^2 \approx \epsilon^{4/3} \mathcal{V}^{1/3}$, so sugra approx $\Rightarrow \epsilon^{4/3} \mathcal{V}^{1/3} \gg \ell_s^2$.

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  Douglas, Shelton, Torroba '07

  $$\mathcal{K}(z, \bar{z}) \sim \left[|z|^2 \left(\log \frac{\Lambda_0^3}{|z|} + 1 \right) + \frac{9c'(g_s M)^2}{(2\pi)^4 \mathcal{V}^{2/3}} |z|^{2/3} \right]$$

  Usually assumed that second term dominates, but large volume can suppress this warping contribution – we will assume regimes of parameter space where first term is also significant.

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  $$W^{cs}/M_p^3 \sim \left[W_0 - \frac{M}{2\pi i} z \left(\log \frac{\Lambda_0^3}{z} + 1 \right) - i \frac{K}{g_s} z \right] .$$

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- Antibrane uplift – *note suppression via small* $|z|$:

  $$V_{\overline{\mathrm{D3}}} = c_{\mathrm{D3}} \left(\frac{g_s^3}{8\pi} \right) \frac{2}{\mathcal{V}^2} \left\{ 1 + \frac{1}{(2\pi)^4} \frac{2}{c''} \frac{(g_s M)^2}{\mathcal{V}^{2/3} |z|^{4/3}} \right\}^{-1} M_p^4 .$$

Deformation modulus stabilisation

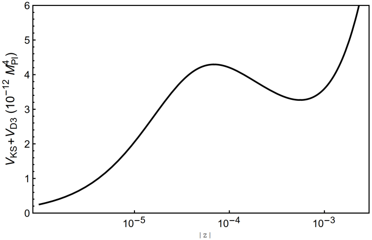
Find minimum in weak warping expansion $1/\beta$:

$$\beta \equiv \frac{\mathcal{V}^{2/3}|z|^{4/3}}{(g_s M)^2}\frac{(2\pi)^4}{c'}\log\frac{\Lambda_0^3}{|z|}$$

with weak warping $\Leftrightarrow \beta \gg 1$:

$$|z|_{min} \approx |z|_{\text{GKP}} \cdot \exp\left\{-c_{\text{D3}}\frac{4K}{3\pi^2 c' M |z_{\text{GKP}}|^{4/3}\mathcal{V}^{2/3}}\right\}$$

$\Rightarrow$ a small shift away from GKP background.



Parameters: $\Lambda_0 = 0.43$, $g_s = 0.17$, $M = 16$, $K = 2$, $\mathcal{V} = 10^4 \Rightarrow$
solutions: $|z|_{min} \approx 5.57 \times 10^{-4}$ and $|z|_{max} \approx 6.89 \times 10^{-5}$.

Weakly-warped LVS dS solution

Embed in LVS scenario with $\mathcal{V} = \tau_b^{3/2} - \kappa_s \tau_s^{3/2}$:

$$\Delta\mathcal{K}/M_p^2 = -2\log\left[\mathcal{V} + \frac{\xi}{2}\right] \text{ and } W = W^{cs} + Ae^{-\frac{a}{g_s}T} .$$

Balasubramanian, Berglund, Conlon & Quevedo '05

In weakly warped regime, $\beta \gg 1$, find dS solution:

$$\mathcal{V} \approx \tau_b^{3/2} = \frac{3(a\tau_s - g_s)}{4a\tau_s - g_s} \cdot \frac{W_0 g_s \kappa_s \sqrt{\tau_s}}{aA} \cdot e^{\frac{a}{g_s}\tau_s} ,$$

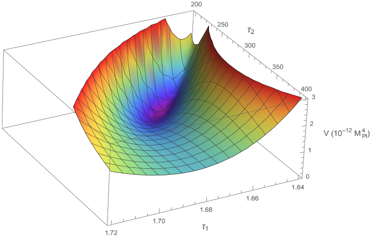
$$\tau_s^{3/2} \approx \frac{\xi}{2\kappa_s} + \frac{g_s}{3a} + \frac{8||\Omega||^2\mathcal{V}}{9g_s\kappa_s W_0^2} + \mathcal{O}\left(\frac{1}{\beta}\right) ,$$

$$\zeta_{min} \approx \zeta_{\mathrm{GKP}} \cdot \exp\left\{-c_{\mathrm{D3}}\frac{4K}{3\pi^2 c' M \zeta_{\mathrm{GKP}}^{4/3}\mathcal{V}^{2/3}}\right\} .$$

provided that:

$$\frac{16||\Omega||^2 a}{27\kappa_s}\left(\frac{2\kappa_s}{\xi}\right)^{1/3} < \frac{g_s^2 W_0^2}{\mathcal{V}} < c_{\mathrm{D3}}\frac{8a||\Omega||^2}{9\kappa_s\sqrt{\tau_s}} .$$

A new dS solution?



W_0	σ	g_s	M	K	Λ_0	κ_s	χ	a	A
2000	0	0.17	16	2	0.43	$\frac{\sqrt{2}}{9}$	-280	$\frac{\pi}{3}$	870

τ_s	τ_b	ζ	$\mathcal{V}$	V_{crit}
1.80	239	4.17×10^{-4}	3684	1.70×10^{-13}

$m_1^2 \sim m_\zeta^2$	$m_2^2 \sim m_{\tau_s}^2$	m_3^2
9.23×10^{-5}	4.87×10^{-4}	4.32×10^{-11}

M_s	m_{KK}	$m_{3/2}$	M_s^w	m_{KK}^w	$m_{3/2}^w$
4.96×10^{-3}	1.26×10^{-3}	1.11×10^{-3}	2.87×10^{-3}	1.74×10^{-3}	6.40×10^{-4}

Subleading corrections

Bento, Chakraborty, SLP & Zavala '23;
see Junghans '22 for strongly warped case;
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- Several further corrections are known - *KK modes, backreaction effects, curvature corrections from fluxes, warping and branes, ...*

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- Compute $\Delta\mathcal{K}$, ΔW and $V(|z|, \tau_b, \tau_s)$; then $\langle\tau_b\rangle$, $\langle\tau_s\rangle$, $\langle|z|\rangle$, $\langle V\rangle$.
- Corrections to vevs:

$$
\begin{aligned}
V_{min} \quad \sim \quad & \alpha - 1 + \mathcal{O}(g_s) + \mathcal{O}(1/\beta) \\
& - C_s^{KK} \cdot \frac{g_s^2}{6\kappa_s}\left(\frac{\hat{\xi}}{2\kappa_s}\right)^{-2/3} + C_s^{log} \cdot \frac{a}{6}(11 + 12\log\nu) + C_1^{\xi} \cdot \frac{a\log\nu}{\kappa_s}\left(\frac{\hat{\xi}}{2\kappa_s}\right)^{-1/3} \\
& - C_2^{\xi} \cdot \frac{g_s}{3\hat{\xi}} - C_{flux} \cdot \frac{10a}{9\kappa_s}\frac{KM}{\mathcal{V}^{2/3}}\left(\frac{\hat{\xi}}{2\kappa_s}\right)^{-1/3} - C_F \cdot \frac{16a}{27\kappa_s}\frac{g_s W_0^2}{\mathcal{V}^{2/3}}\left(\frac{\hat{\xi}}{2\kappa_s}\right)^{-1/3} \\
& - C_b^{KK} \cdot \frac{8c' a(g_s M)^2}{9\kappa_s}\frac{g_s \zeta^{2/3}}{\mathcal{V}^{1/3}}\left(\frac{\hat{\xi}}{2\kappa_s}\right)^{-1/3} + C^{con} \cdot \mathcal{O}(1/\beta^3)\,.
\end{aligned}
$$

with $\nu = \frac{3g_s\kappa_s W_0}{8aA}\left(\hat{\xi}/(2\kappa_s)\right)^{1/3}$.

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- Compute $\Delta\mathcal{K}$, ΔW and $V(|z|, \tau_b, \tau_s)$; then $\langle\tau_b\rangle$, $\langle\tau_s\rangle$, $\langle|z|\rangle$, $\langle V\rangle$.
- Corrections to vevs:

$$\begin{aligned} V_{min} \quad \sim \quad & \alpha - 1 + \mathcal{O}(g_s) + \mathcal{O}(1/\beta) \\ & - C_s^{KK} \cdot \frac{g_s^2}{6\kappa_s}\left(\frac{\hat{\xi}}{2\kappa_s}\right)^{-2/3} + C_s^{log} \cdot \frac{a}{6}(11 + 12\log\nu) + C_1^{\xi} \cdot \frac{a\log\nu}{\kappa_s}\left(\frac{\hat{\xi}}{2\kappa_s}\right)^{-1/3} \\ & - C_2^{\xi} \cdot \frac{g_s}{3\hat{\xi}} - C_{flux} \cdot \frac{10a}{9\kappa_s}\frac{KM}{\mathcal{V}^{2/3}}\left(\frac{\hat{\xi}}{2\kappa_s}\right)^{-1/3} - C_F \cdot \frac{16a}{27\kappa_s}\frac{g_s W_0^2}{\mathcal{V}^{2/3}}\left(\frac{\hat{\xi}}{2\kappa_s}\right)^{-1/3} \\ & - C_b^{KK} \cdot \frac{8c' a (g_s M)^2}{9\kappa_s}\frac{g_s \zeta^{2/3}}{\mathcal{V}^{1/3}}\left(\frac{\hat{\xi}}{2\kappa_s}\right)^{-1/3} + C^{\text{con}} \cdot \mathcal{O}(1/\beta^3)\,. \end{aligned}$$

with $\nu = \frac{3 g_s \kappa_s W_0}{8aA}(\hat{\xi}/(2\kappa_s))^{1/3}$.

- Consistent dS vacuum needs C to be small – we need to compute these...

Transient de Sitter via interacting Dark Sectors

Elephant in the Room by Banksy

Claim: interacting Dark Sector can source a transient dS with small field displacements and no fine-tuning between potential parameters or in initial conditions, consistently with string swampland conjectures.

Interacting Dark Sectors

Gomes, Hardy & SLP, to appear

Toy model - two interacting dark scalar fields:

$$\mathcal{L} = \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi + \frac{1}{2} g^{\mu\nu} \partial_\mu \psi \partial_\nu \psi + V(\phi, \psi) \; ,$$

with canonical kinetic terms and a scalar potential of the form:

$$V(\phi, \psi) = V(\phi) + \frac{1}{2} m_\psi^2 \psi^2 + \frac{1}{2} \frac{m_{\text{int}}^2}{\Lambda^2} \phi^2 \psi^2 \; .$$

and Higgs-like hilltop or runaway potential for ϕ:

$$V(\phi) = \rho_{\text{de}} \left(\left(\frac{\phi}{\Lambda} \right)^2 - 1 \right)^2 \quad \text{or} \quad V(\phi) = \rho_{\text{de}} \, e^{-\frac{\phi}{\Lambda}}$$

With $m_{\text{int}} = 0$ either ϕ or ψ could source slowly-rolling quintessence... but only with fine-tuning to hilltop or dangerous large field distances.

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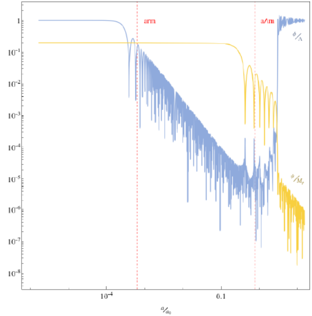
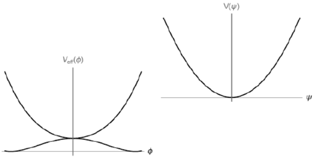
With $m_{\rm int} \neq 0$ and ψ behaving as DM, DR or subdominant DE - can stabilise ϕ near $\phi = 0$ to source observed DE as transient dS!

A transient de Sitter

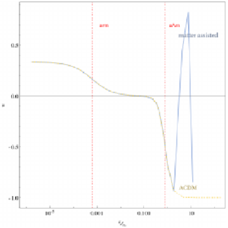
Dvali & Kachru '03, Copeland & Rajantie '05, Axenides & Dimoloulos '04 'Locked Inflation/Dark Energy', Gomes, Hardy & SLP to appear

- Cosmological background $\psi(t) = \psi_0 e^{-3H(t-t_0)/2} \cos(m_\psi t)$; collection of scalar particles oscillating coherently.
- Background in $\frac{1}{2}\frac{m_{\rm int}^2\langle\psi^2\rangle}{\Lambda^2}\phi^2$ creates false vacuum at $\phi = 0$ where $V_{\rm min} = \rho_{\rm de}$ until exit via parametric resonance – analytic understanding via Mathieu's equation.





$$\frac{\Lambda}{M_{\rm pl}} = 0.1,\ \frac{m_{\rm int}}{H_0} = 10^5,\ \frac{m_\psi}{H_0} = 10,\ \frac{\psi_0}{M_{\rm pl}} = 0.4,\ \frac{\dot{\phi}_0}{\Lambda} = 1.$$



- No tuning of initial conditions, no super-Planckian distances, a transient dS with no fine-tuning in Lagrangian parameters!

Outlook

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- String model to be worked out... leaves the cc problem...

DM Assisted DE – parameter space

Gomes, Hardy & SLP to appear